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Evaluation of a Portable Shock Tube for Function Testing of Air Blast Pressure Transducers

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and A. Pleckauskas

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ABSTRACT

Tests were conducted on a portable shock tube to study the pressure-time profile emanating from the open end of the tube and its suitability for function testing of pressure transducers in the field *in situ*. The pressure pulse was generated from a 0.22 calibre blank cartridge and a piezoelectric pressure transducer was used to record the signal. Comparisons were made between the pressure-time profiles generated by three types of cartridge representing three different pressure loadings. The shock tube was used in several mounting configurations, and tube design modifications were made to improve its performance. The resultant pressure profiles were compared to profiles generated from a starting pistol. Recommendations are made on the features of the pressure profile necessary for calibration and modifications are proposed which should enable these features to be produced.

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Executive Summary

A portable shock tube, used for function testing pressure transducers *in situ*, was evaluated. Experiments were conducted in which several pressure levels were generated and recorded. The results indicated that the portable shock tube is simple to operate and pressure levels up to 700 kPa (100 psi) are generated easily and quickly. Thus the portable shock tube has added to our capability by enabling the generation of higher pressure levels, above 35 kPa, compared to previous methods. This work was undertaken for the Ship Survivability Enhancement Program (SSEP), in which a series of air blast experiments were conducted inside compartments on a decommissioned RAN vessel, the Derwent. Air blast overpressure measurements were an essential part of the experiments, undertaken to quantify the structural loading from the explosion. The evaluation of the portable shock tube also has proven significant to other tasks requiring the modelling of the survivability of naval platforms to explosive events. These models require measurements of air blast pressure closer to the explosion and the use of the portable shock tube has led to the acquisition of higher quality results.

Authors

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George Yiannakopoulos completed Bachelors of Mechanical Engineering and Science in 1982 and 1985 respectively. He has been with AMRL since 1986 and during this time he has been involved in the measurement of shock wave phenomena including underwater pressure measurements, air blast and shock induced motion. Currently Mr Yiannakopoulos works in the Ship Structures and Materials Division.

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Algis Pleckauskas has been with AMRL for nearly forty years and during this time he has participated in many laboratory experiments and field trials in support of explosive measurements. These measurements have covered many areas including air blast overpressures, detonation noise, acceleration, fragmentation velocities related to explosives and ammunitions, shock testing of naval vessels, strain and velocity measurements. He has been involved, not only in carrying out measurements, but also in the development of electronic instrumentation for this work and in assisting in the planning and execution of large scale defence trials. He currently works in the Ship Structures and Materials Division.

Contents

1. Introduction

Field measurements of air blast overpressure require function testing of pressure transducers *in situ* prior to the event. The test is a diagnostic tool aiding in the detection of instrumentation faults such as a damaged transducer, broken cable or a faulty line power unit. Function testing is an essential part of the experimental procedure. Ideally such tests should be carried out before and after each experiment but this is usually dictated by time constraints.

Function testing in the field is currently performed by a starting pistol, utilising powder caps. This generates a pressure up to 70 kPa, depending on the distance between the transducer and starting pistol, which simulates a typical profile from above ground detonation of explosives and is generated easily, quickly and safely. The profile consists of a sharp rise to the peak value, with a typical rise time of 5 μs, followed by an exponential decay, followed by a negative phase and then a positive phase. The method has been used successfully over the years for transducers with a maximum range of 7 MPa.

Recently there has been an increasing demand at AMRL to measure the blast parameters closer to the explosive. To achieve this a number of different transducers have been introduced with maximum ranges between 35 MPa and 600 MPa. These transducers have lower sensitivities and consequently are insensitive to the low pressure levels generated from the starting pistol powder caps. However, function testing is an important part of data acquisition, and to ensure valid data a pressure source was sought that could generate a significantly higher pressure to produce a higher voltage output.

AMRL procured a portable shock tube from Applied Research Associates Inc. (ARA), in USA, which met this need and has been used by Defence Research Establishment, Suffield (DRES) in Canada for this purpose. It was particularly useful for the Ship Survivability Enhancement Program during which a series of air blast experiments were conducted inside designated compartments on a decommissioned RAN vessel, the Derwent. Some of the locations required pressure transducers with ranges at 35 MPa which were insensitive to pressure levels generated by the starting pistol. The experiments were expected to result in severe damage to the ship's equipment and therefore there was a high risk of transducer damage, especially from fragments. The trial demanded a tight schedule requiring each transducer to be tested quickly between events.

The evaluation consisted of tests on the ARA portable shock tube by using powder cartridges of various strengths. The tests indicated that the portable shock tube is simple to operate and pressure levels up to 700 kPa (100 psi) are generated easily and quickly. Thus it proved convenient to use in the field for function testing of air blast transducers *in situ*. However, in comparison, a starting pistol, in the side-on configuration, produces a pressure pulse free of powder debris and thus provides more information on the transducer response even though the levels are much lower, typically 30-70 kPa. Information provided includes

transducer rise time, decay time constant, overshoot, hysteresis and ringing of the pressure transducer.

2. Aim

The aim was to develop suitable testing equipment for the use of function tests for pressure transducers with higher range. Firstly, it was required to test the portable shock tube using three different colour-coded 0.22 calibre blank cartridges, representing different charge weights purchased from a local Melbourne supplier, and compare these to results generated from similar tests conducted by DRES [1]. Although cartridges are available locally, there was insufficient information from both the US manufacturer and the local agent to identify the explosive strength of each cartridge type and therefore correlate the colour codes. Therefore these tests were conducted to measure the peak pressures from the respective colour coded cartridges.

Secondly it was sought to improve the pressure profile emanating at the open end of the shock tube and to augment the work conducted at DRES. The profiles generated consisted of multiple shock waves. It is essential to generate profiles that have repeatable peaks, are well characterised and are clean, free of reflections and powder debris. Repeatable peaks can indicate whether the transducer sensitivity has altered. A well characterised profile can help diagnose electrical and electronic faults such as cable damage and amplifier response. Clean profiles provide information about the rise time and overshoot of the transducer. Therefore modifications were made to the shock tube in an attempt to achieve these features.

Thirdly it was sought to generate pulses similar to that from the starting pistol but at higher peaks, involving both a positive and negative shock wave phase. The negative phase, a rarefaction wave, is not generated when the shock tube is placed directly above the transducer since it forms a seal and the air cannot expand. Furthermore reflections occur only from the rigid boundaries at both ends. It is useful in function tests to subject the transducer to both compressive and rarefaction waves so that transducer hysteresis effects can be identified.

Finally, in its present form the portable shock tube generates a pressure pulse with multiple shock waves arising from reflections inside the tube and resonance from powder debris. There is a requirement for modifications to achieve a clean, repeatable and well characterised profile. Consideration is given to modifying the shock tube to obtain a sensitivity and to determine transducer characteristics such as rise time, decay time constant, overshoot and ringing. Ideally this information can be obtained from a pressure-time profile depicted in Figure 1. However this is intended to be the subject of another investigation.

3. Experimental

The portable shock tube consists of a dummy launcher and an aluminium tube with a 50 mm bore, 800 mm long, Figure 2. The launcher, a commercial product for dog retrieval training, is designed to propel a PVC oval or canvas cylinder dummy which is the component that is retrieved. The launcher forms the driver end of the shock tube and consists of a pin, at one end, and chamber, at the other, to fire a .22 calibre blank cartridge. The gaseous products from the cartridge exit the launcher from the side rather than centrally. The end of the shock tube is covered by a rubber sleeve to isolate the aluminium tube from the surface in which the transducer is mounted. When triggered it produces a high noise output, particularly when fired with an air gap between the end of the tube and the transducer, and of sufficient intensity to necessitate the wearing of hearing protection. The portable shock tube is described in the preliminary work undertaken by DRES [1].

The instrumentation used to record the data is shown in Figure 3, and consisted of a ATS Digistar III recorder connected to a Toshiba 3200SX laptop. A PCB 102A02 pressure transducer was mounted in a lead block and positioned on a concrete floor.

To evaluate the performance of the shock tube in terms of the blast parameters produced, six different mounting configurations were used, Figure 4, and were as follows:

Configuration 1

The portable shock tube was butted vertically against the lead block containing the pressure transducer to measure reflected pressure. The aim was to compare the pressure levels from the different cartridges.

Configuration 2

The starting pistol was fired at the edge of the lead block to measure side-on pressure. This was a comparison illustrating the previous method of function testing transducers and the desirable features in a pressure profile in these tests.

Configuration 3

The starting pistol was fired directly above the lead block and transducer to measure reflected pressure. This was conducted to demonstrate the disadvantage of the starting pistol by showing that it is useful only for side-on measurements. The results illustrate the effects of powder debris strikes on the transducer.

Configuration 4

The portable shock tube was fired horizontally along the edge of the lead block to measure side-on pressure. The aim was to obtain a smoother profile, to generate a negative phase and to determine the attenuation of the pressure level.

Configuration 5

The portable shock tube was placed vertically above the lead block and pressure transducer, with an air gap, to measure reflected pressure. The aim was to obtain a smoother profile.

Configuration 6

The portable shock tube was placed vertically above the lead block and pressure transducer, with the rubber sleeve extended to measure reflected pressure. The difference between this configuration and configuration 1 was that the rubber sleeve butted directly onto the lead block to form a seal thereby minimising any venting and effectively increasing the length of the shock tube. The aim was to obtain a smoother profile.

Thirty-four firings were conducted and the results are summarised in Table 1. The first series (shots 1-9) involved configuration 1, using green (shots 1-3), yellow (shots 4-6) and red (shots 7-9) cartridges to determine the magnitude and repeatability of the pressure levels generated. Starting pistol firings were carried out to measure side-on pressure (shots 10-12) and reflected pressure (shot 13). The stand-off distance was 100 mm in a horizontal and 200 mm in the vertical orientation, respectively.

The next series (shots 14-22) were a repeat of shots 1-9 but using the shock tube modified with a polyurethane backing material. A number of different length PVC insert sleeves were then placed around the exhaust hole of the dummy launcher; a 50 mm sleeve (shot 23) and then a 160 mm sleeve (shot 24). The 160 mm sleeve was used for the side-on measurements (shots 25-26), using configuration 4. The shock tube was located at a distance of 100 mm from the transducer and raised 5 mm above the lead block (shot 25) and at 90 mm with the open end of the shock tube resting directly on the lead block (shot 26).

The shock tube was then oriented vertically above the transducer, configuration 5, with an air gap (shots 27-31). The 100 mm PVC sleeve was retained and the air gap varied; 25 mm for shot 27 and 50 mm for shot 28. The sleeve was removed and the tests (shots 29-31) were repeated using only a 50 mm air gap.

A polystyrene backing was then placed inside the shock tube (shots 32-34) which was fired directly above the transducer with no air gap (shots 32-33) and then with the rubber sleeve extended (shot 34).

4. Discussion

Peak pressures are presented, together with the pressure source and configuration, Table 1. Plots of the pressure-time profiles are presented in Figure 5.

4.1 Comparison between the colour-coded cartridges.

Shots 1-9 are plotted on a 10 ms window to illustrate the reflections from the boundary ends. The relative peak pressures between the different cartridges can be seen; the green cartridges being the lowest with the red being the highest. The yellow cartridges have levels somewhere in between these but the peak levels vary considerably. The multiple reflections are those expected from a conventional shock tube in which the shock wave reflects back and forth from the rigid boundary ends till it eventually dies out. The number of reflections in the 10 ms window is consistent with the pressure levels; that is the shock transit time is shorter for higher pressures. The green cartridges, which produce the lowest pressure levels, only generate three pulses while the yellow (shots 4 and 6) and the red cartridges show four pulses, with the energy being almost dissipated in the fourth pulse.

The results from the green cartridges and to some extent from the yellow, exhibit some resonance compared to results from the red cartridges which are cleaner. The resonance is probably present in the red cartridges, but because the levels are relatively higher the effect is not as noticeable.

Overall the results presented are similar to those obtained by DRES with rise times of 5 to 6 μs and positive phase duration between 2 and 3 ms. They also report that the cartridges, irrespective of charge weight, produce variable pressure levels and this was confirmed in our tests.

4.2 Starting pistol results.

The pistol shots fired side-on produced cleaner, repeatable and well characterised peaks with positive and negative phases (Figure 5, shots 10-12). The decay is almost exponential and there is both a positive and negative phase. These features show that the starting pistol provides a suitable means to test the proper functioning of the transducers in the field.

On the other hand, firing the pistol directly above the transducer (shot 13) resulted in powder debris striking the transducer producing a noisy profile. The result is not considered useful for function testing the transducers and therefore this configuration was not pursued further. However it does illustrate the effect of powder debris impinging on the transducer and the consequent spikes in the negative phase make this phase difficult to discern. Similar spikes due to the combustion by-products are observed in shots 1, 2, 7 and

are more evident in shots 29-31. This is an undesirable feature and can be erroneously attributed to poor transducer response.

4.3 AMRL modifications to the portable shock tube.

The results from the side-on pistol shots motivated modifications to the shock tube to generate a clean and well characterised profile. The first modification aimed to reduce reflections at the rigid wall boundary at the driver end by minimising wave interactions, by using acoustic impedance matching and shock attenuation. Backing material was placed behind the exhaust hole, Figure 6, moving the end boundary closer to the exhaust hole thereby minimising side reflections from the aluminium tube. Matching the impedance of the boundary and air reduces or eliminates the amplitude of the reflected wave. The transmitted wave through this backing material would also be attenuated. Results showed that this modification eliminated the second reflection in the incident profile (Figure 5, shots 14-22). However the gain was marginal and it did not reduce the large second peak observed.

Minimising the second peak proved more difficult and a number of techniques were investigated. It was assumed that the second peak was attributed to reflections caused by the gaseous products emitted from the exhaust hole and interacting with the immediate aluminium wall. Clearly the backing material was not the answer. Placing the PVC tube around the exhaust hole was then considered a possible solution to reduce these reflections. In effect a miniature shock tube was constructed the aim being to reduce the reflection from the exhaust hole by merging the multiple shock waves as they decreased in speed down the tube to form a single wave. It is evident from the profiles that there is some reduction in the second peak and that the addition of the sleeve has no determinate effect on the magnitude or duration of the first peak, Figure 5 (shots 23-24).

When the shock tube was fired horizontally (shots 25-26), Figure 4, configuration 4, a negative phase was generated and the second peak was reduced significantly but not entirely eliminated. The profile consisted of multiple waves; the decay was not exponential, and the negative phase dropped sharply. The peak pressure was reduced considerably from about 700 kPa to about 70 kPa, making this configuration unsuitable for function testing transducers with high pressure ranges.

The side-on firings showed a reduction in the magnitude of the second peak, clearly indicating that the cause of this peak is the open end of the shock tube, at the rubber sleeve. To overcome this effect the shock tube was oriented vertically above the transducer with an air gap. A 25 mm air gap improved the overall profile but the pressure level was reduced by 20 %. A 50 mm air gap resulted in no further improvement in the profile but there was a reduction in the peak pressure by 40-50 %.

Polystyrene was used as an alternative backing material and it seems to have improved the profile slightly, reducing the magnitude of the secondary peaks. However the profile is still unacceptable for function testing due to the multiple waves. In the final shot, extending the

rubber sleeve caused multiple peaks, again showing no appreciable improvement in the profile.

5. Recommendations

Our tests have shown that the second peak emanates from the open end of the shock tube. This was later confirmed from subsequent investigations conducted at DRES [2], where a computer simulation using a 2-D geometric ray tracing model [4] showed that the second peak arises from the small step between the rubber sleeve and aluminium tube. We intend to conduct further experiments to confirm their results.

The conclusion from these tests is that the portable shock tube can be used as a calibrator for field applications. This is verified by the subsequent work conducted at DRES [2] which improved the profile by three modifications; the use of an expansion cone, mounting the rubber sleeve flush with the aluminium tube and placing the transducer near the edge of the open end. The cone, diverging by 18°, was placed around the dummy launcher hole, similar to the PVC sleeve used in our tests.

However, further modifications are required to produce a profile for calibration. Ideally this should result in a pressure profile with a step rather than a single peak value as generated by a conventional shock tube, Figure 1. Altering the shock tube dimensions to meet this requirement will be the subject of further studies and will involve computer modelling. This step profile will enable the accurate determination of the sensitivity of the transducer and quantify the transducer response and characteristics.

The portable shock tube, with the modifications for a calibration pressure profile, would be used as in configuration 1 to generate a reflected pressure. To determine the sensitivity, further modifications will require the measurement of the shock transit time as well as measurements of ambient temperature and pressure [3] (Appendix I). Shock transit time measurements can be performed by piezoelectric pin probes attached to the shock tube. A thermocouple and barometer can also be attached to measure ambient temperature and pressure.

6. Conclusion

Tests were conducted to evaluate the performance of the ARA portable shock tube. It is simple to operate and can generate pressure levels up to 700 kPa (100 psi), easily and quickly. Thus it is convenient to use in the field for function testing of air blast transducers *in situ*. However in comparison, a starting pistol produces a cleaner pressure pulse and provides more information on the transducer response even though the levels are much lower, typically 30-70 kPa (5-10 psi). Furthermore the starting pistol is smaller, lighter, more

portable and hence more convenient to use. Information provided from the starting pistol includes transducer rise time, decay time constant, overshoot, hysteresis and ringing.

A disadvantage of the portable shock tube is that the pressure levels generated from the different cartridges do not produce repeatable pressure levels irrespective of the cartridge type used. This is most likely a function of variations in charge weight, as the cartridges are used for commercial building purposes.

The tests indicated that best results are obtained for the portable shock tube by inserting backing material behind the exhaust hole and firing it in a vertical orientation with an air gap of approximately 25 mm. Even though repeatable peaks were not obtained nor was the profile sufficiently smooth with an exponential decay, the profile is sufficiently characterised for transducer function tests. Therefore further modifications are required if it is to be used for calibration in the field. Ideally a pressure step is required that is clean of powder debris and reflections. Time of arrival sensors will need to be added to measure the shock transit time together with ambient measurements to calculate reflected pressure enabling the determination of the transducer sensitivity.

7. Acknowledgments

The authors would like to thank Mr John Keefer from Applied Research Associates Inc. for the loan of the portable shock tube, Mr D. Ritzel from DRES for helpful discussions and for making available papers on tests conducted at DRES, and Dr N. Burman for encouragement and support of this work.

8. References

[1] Campbell R. L. (1993), Portable Shock Tube Output and Waveform Tests, Transducer Lab Technical Note no. 3, DRES (internal publication).

[2] Campbell R. L. (1994), Portable Shock Tube DRES Modifications and Improvements, Research Note no. 1445, DRES (internal publication).

[3] ANSI B88.1-1972, A Guide for the Dynamic Calibration of Pressure Transducers, 8 August 1972, p 11.

[4] Thibault P. and Sulmistras A. "Fluid Dynamics/Blast Prediction and Structural Response Workstation", Combustion Dynamics Ltd, Medicine Hat AB, Canada, 1991.

Appendix

Calibration of Pressure Transducers by a Shock Tube

Calibration of pressure transducers requires the determination of a sensitivity, s [V/Pa] which is obtained by measuring the peak voltage of the profile, V_P, from the profile generated by the shock tube and by calculating the peak reflected pressure, ΔP [Pa], that is:

$$s = \frac{V_P}{\Delta P} \qquad \text{A-1}$$

The peak reflected pressure can be calculated using the following expression:

$$\Delta P = \frac{7}{3} P_o \left(M_S^2 - 1\right)\left(\frac{2 + 4M_S^2}{5 + M_S^2}\right) \qquad \text{A-2}$$

where P_o denotes the ambient absolute pressure, M_S the Mach number. M_S is determined from the velocity of the shock wave, v [m/s] and the local sound speed, c [m/s], as follows:

$$M_S = \frac{v}{c} \qquad \text{A-3}$$

The velocity of the shock wave can be calculated by assuming that it is approximately equal to the average velocity, v_{av}, requiring the measurement of the shock transit time, Δt [s], over a distance interval, Δd [m], that is:

$$v_{av} = \frac{\Delta d}{\Delta t} \qquad \text{A-4}$$

The local sound speed is obtained from the measurement of ambient temperature, T [K], and by using the isentropic relationship:

$$c = \sqrt{\gamma R T} \qquad \text{A-5}$$

where $\gamma = 1.4$ for and $R = 287$ J/kg K for air.

The above analysis applies only to shock waves in air and assumes that the products from the cartridge have minimal effects on the properties of the fluid in the vicinity of the transducer. These properties include density and the ratio of specific heats, γ. The validity of this assumption will need to be tested.

Table 1: Summary of pressure levels from the Portable Shock Tube (PST).

Colour Code	Shot Number	Peak Pressure (psi)	(kPa)	Source/ Configuration	Comments
Green	1	20	140	PST / 1	Cartridge comparison.
Green	2	25	170	PST / 1	Repeat of 1.
Green	3	35	240	PST / 1	Repeat of 1.
Yellow	4	95	655	PST / 1	Repeat of 1.
Yellow	5	40	280	PST / 1	Repeat of 1.
Yellow	6	82	570	PST / 1	Repeat of 1.
Red	7	120	830	PST / 1	Repeat of 1.
Red	8	80	550	PST / 1	Repeat of 1.
Red	9	112	770	PST / 1	Repeat of 1.
Cap	10	6.5	45	Pistol / 1	Side-on, 200 mm separation.
Cap	11	5.6	39	Pistol / 1	Repeat of 10.
Cap	12	7.2	50	Pistol / 1	Repeat of 10.
Cap	13	4.8	33	Pistol / 2	Directly above 200 mm.
Green	14	29	200	PST / 2	Polyurethane backing.
Green	15	28	190	PST / 1	Repeat of shot 14.
Green	16	31	210	PST / 1	Repeat of shot 14.
Yellow	17	109	750	PST / 1	Repeat of shot 14.
Yellow	18	112	770	PST / 1	Repeat of shot 14.
Yellow	19	99	680	PST / 1	Repeat of shot 14.
Red	20	124	850	PST / 1	Repeat of shot 14.
Red	21	125	860	PST / 1	Repeat of shot 14.
Red	22	118	810	PST / 1	Repeat of shot 14.
Red	23	101	700	PST / 1	PVC insert 50 mm long.
Red	24	100	690	PST / 1	PVC insert 160 mm long.
Red	25	10	69	PST / 4	Side-on, L=100 mm, D=5 mm.
Red	26	13	90	PST / 4	Side-on, L=90 mm, D=0 mm.
Red	27	80	550	PST / 5	25 mm air gap.
Red	28	58	400	PST / 5	50 mm air gap.
Red	29	67	460	PST / 5	50 mm air gap.
Red	30	48	330	PST / 5	50 mm air gap.
Red	31	63	430	PST / 5	50 mm air gap.
Red	32	108	740	PST / 1	Polystyrene backing.
Red	33	96	660	PST / 1	Polystyrene backing.
Red	34	115	790	PST / 6	Polystyrene backing.

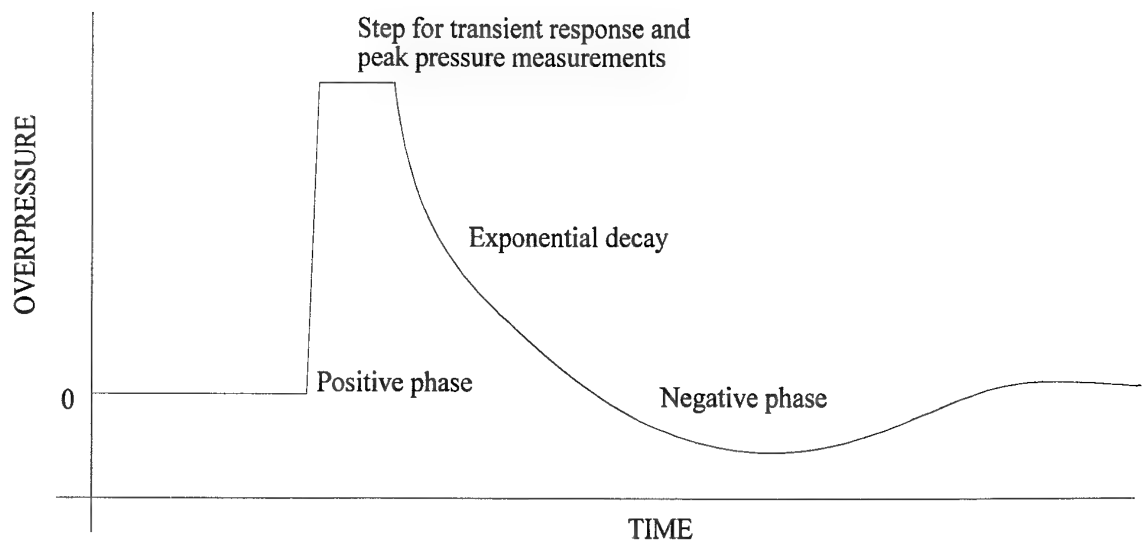

Figure 1 - Recommended pressure profile characteristics for calibration of air blast pressure transducers.

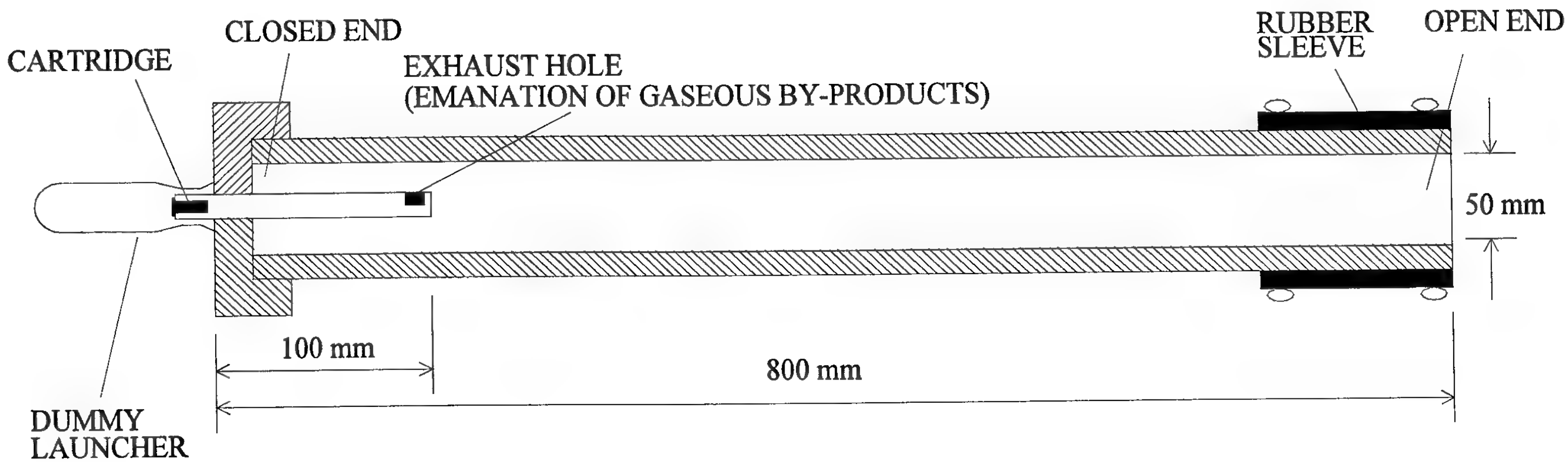

Figure 2 - Schematic of the portable shock tube.

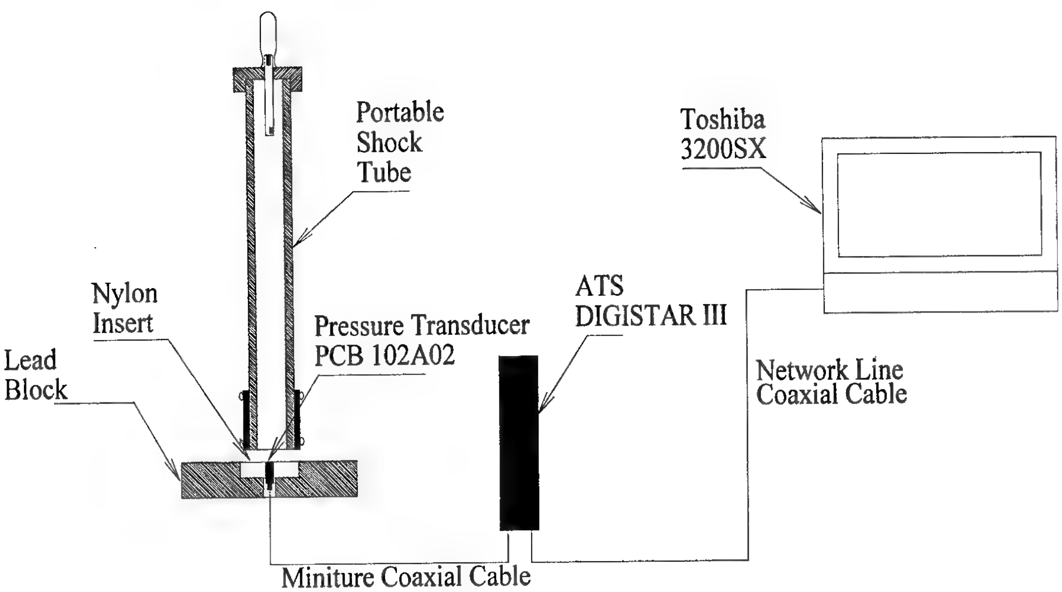

Figure 3 - Schematic of experimental set-up for testing the portable shock tube.

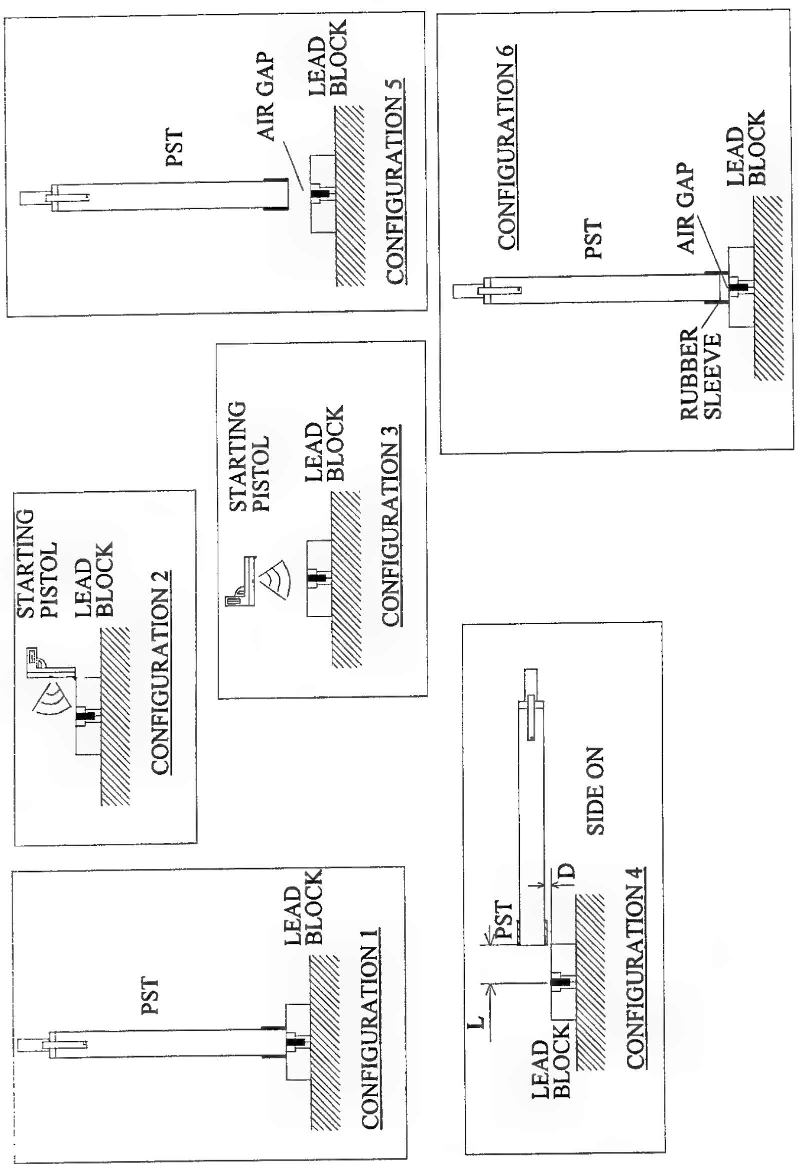

Figure 4 - Configurations used to evaluate the performance of the Portable Shock Tube (PST).

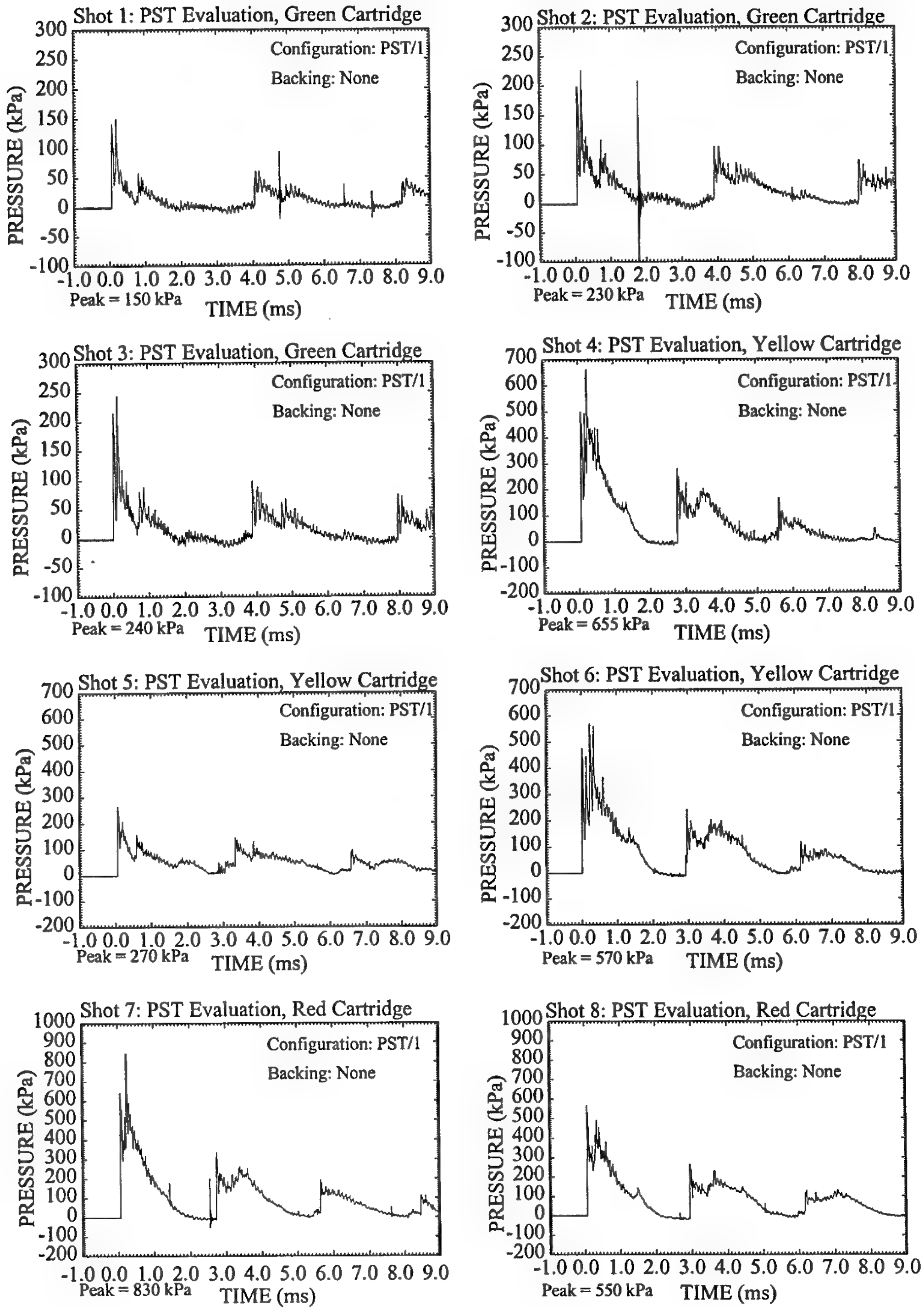

Figure 5 - Pressure-time profiles from the portable shock tube for shots 1 to 8.

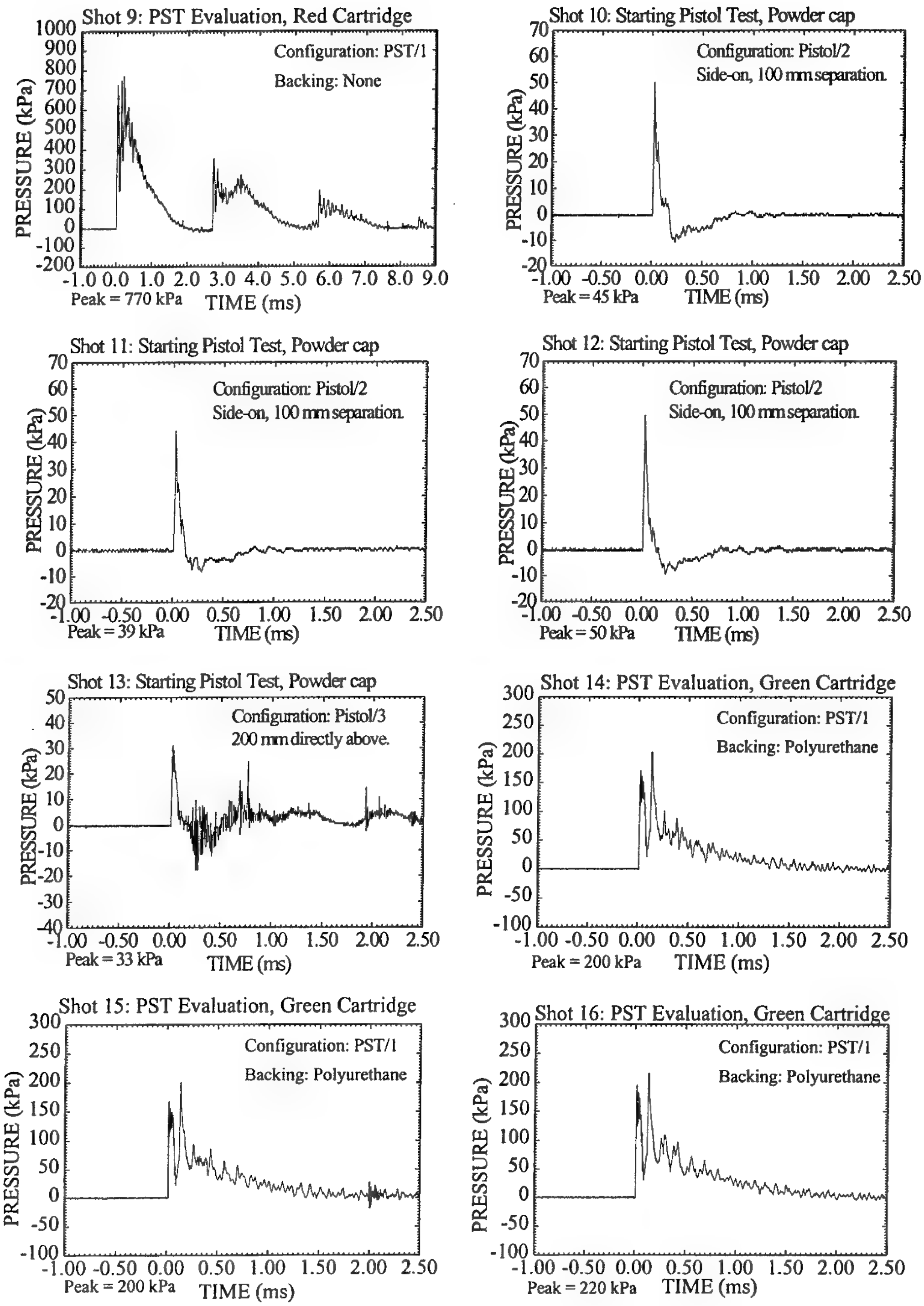

Figure 5 (continued) - Pressure-time profiles from the portable shock tube for shots 9 to 16.

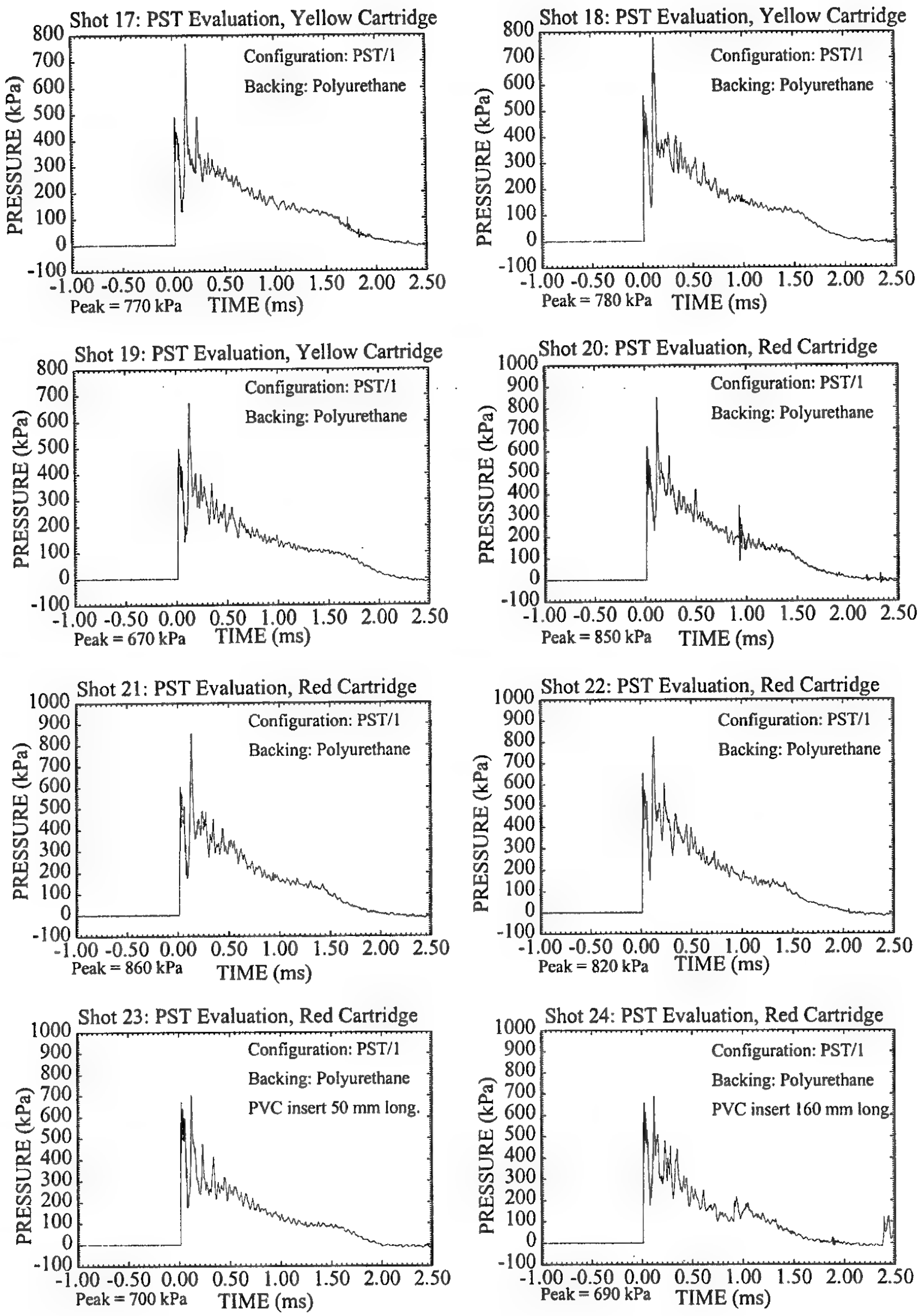

Figure 5 (continued) - Pressure-time profiles from the portable shock tube for shots 19 to 24.

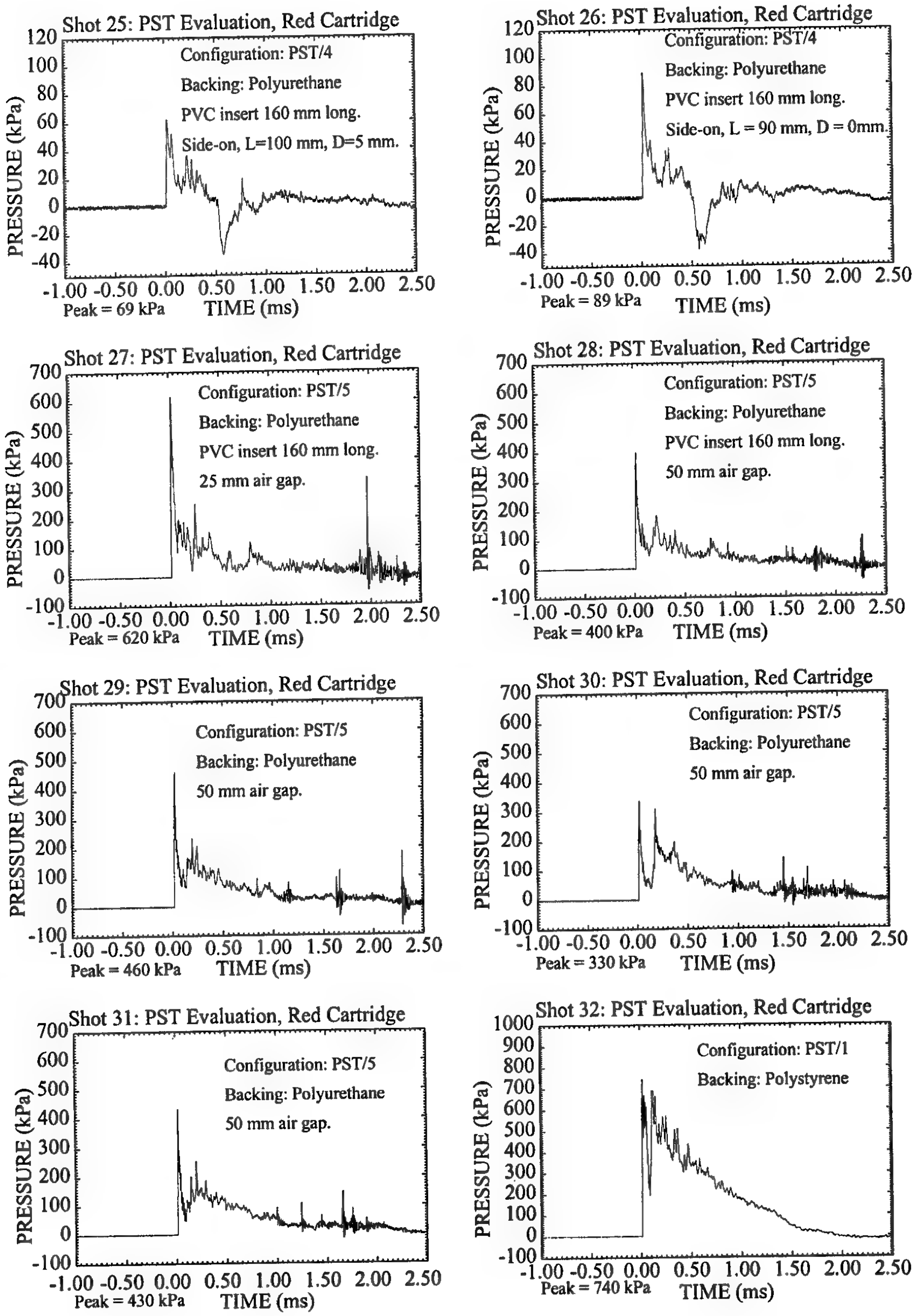

Figure 5 (continued) - Pressure-time profiles from the portable shock tube for shots 25 to 32.

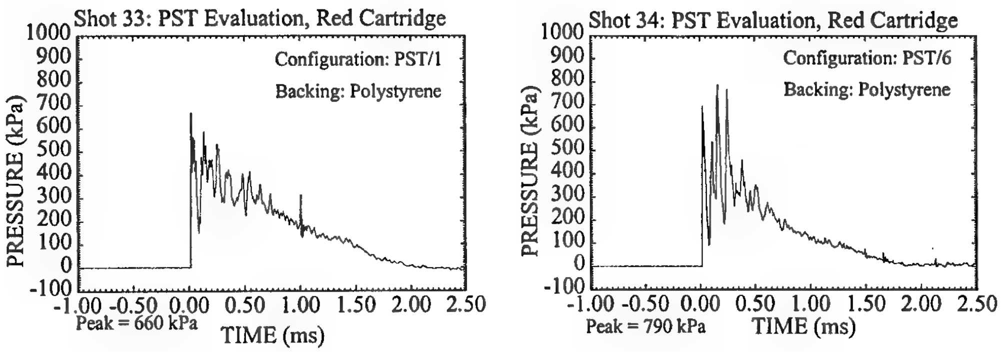

Figure 5 (continued) - Pressure-time profiles from the portable shock tube for shots 33 to 34.

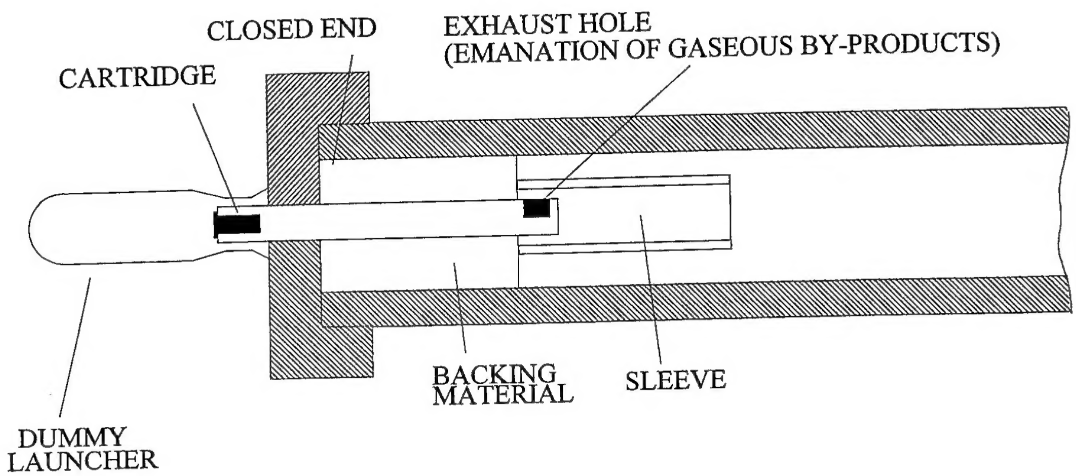

Figure 6 - Modifications to the portable shock tube.

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19. ABSTRACT
Tests were conducted on a portable shock tube to study the pressure-time profile emanating from the open end of the tube and its suitability for function testing of pressure transducers in the field *in situ*. The pressure pulse was generated from a 0.22 calibre blank cartridge and a piezoelectric pressure transducer was used to record the signal. Comparisons were made between the pressure-time profiles generated by three types of cartridge representing three different pressure loadings. The shock tube was used in several mounting configurations, and tube design modifications were made to improve its performance. The resultant pressure profiles were compared to profiles generated from a starting pistol. Recommendations are made on the features of the pressure profile necessary for calibration and modifications are proposed which should enable these features to be produced.